4.0 Longitudinal Countermeasure Sensing/Algorithm Tests

In Task1 of this program, extensive analyses were conducted to characterize the circumstances associated with run-off-road crashes. Results from these analyses indicate that a significant percentage (24.4 percent) of run-off-road crashes occur on curves. The proportion of fatal crashes occurring on curves is even higher (42.4 percent) underscoring the importance of curve related crashes. Table 4-l (originally Table 3-5 in the Task 1 report) examines roadway alignment for fatal vs. all run-off-road crashes.

Table 4-1: Roadway alignment: fatal vs. all run-off-road crashes

Roadway Alignment	FARS		GES	
	Fatal Crashes	% Fatal Crashes	All Crashes	% of All Crashes
Straight	7,653	57.3	857,296	71.1
Curve	5,665	42.4	294,721	24.4
Unknown	29	0.2	53,816	4.5
Total	13,347	99.9	1,205,833	100.0

Moreover, speeding is the most frequent violation charged in association with roadway departures on curves (10.2 percent), according to the General Estimates System (GES 1992) data. When charges of reckless driving are included, this percentage goes up to 14.3 percent. This indicates that unsafe driving acts when approaching curves are an important cause of roadway departure crashes. Table 4-2 (originally Table 5-13 in the Task 1 report) presents data showing violations charged by horizontal alignment.

Table 4-2: Violations charged by horizontal alignment

Violations Charged	Horizontal Alignment		
	Straight	Curve	Unknown
None	56.4	57.8	57.3
Alcohol or Drugs	8.5	8.1	4.8
Speeding	5.2	**10.2**	6.7
Alcohol or drugs & speeding	0.8	1.7	0.7
Reckless Driving	3.4	**4.1**	2.2
Suspended/Revoked License	0.4	0.4	0.0
Failed to yield Right-of-way	0.2	0.0	0.0
Ran signal/stop sign	0.2	0.0	0.2
Hit and Run	10.3	4.2	11.2
Other/Unknown	14.6	13.4	16.8

The detailed clinical analysis of 200 NASS cases conducted for Task 1 also indicates that excessive speed, particularly associated with curves, is a frequent cause of roadway departure crashes. Total of 58.1 percent of the crashes in the clinical sample studied occurred on curved roadway segments. See Table 4-3 (originally Figure 5-12 in the Task 1 report).

Table 4-3: Roadway alignment in SVRD crashes - CDS data (weighted %)

Horizontal Alignment	
Curve Left	**16.2**
Curve Right	**41.9**
Straight	41.9
Total	100.0

The clinical analysis also indicates that excessive speed is the single largest causal factor, accounting for 32 percent of all roadway departure crashes. Table 4-4 (originally Table 5-33 in the Task 1 report) shows that 38.7 percent of all SVRD crashes on curves are caused by excessive speed, indicating that excessive speed is over-represented as a causal factor on curves as compared with the entire population of SVRD crashes.

Table 4-4: Causal factor by horizontal alignment

Causal Factor	Horizontal Alignment	
	Straight	Curve
Driver Inattention	16.9	7.7
Driver Relinquished Steering Control	16.0	24.8
Evasive Maneuver	20.0	10.8
Lost Directional Control	16.9	15.0
Vehicle Failure	4.1	3.2
Vehicle Speed	26.1	38.7
Total	100.0	100.0

Based on these Task 1 findings, the project team determined that a system which could warn the driver of excessive speed for the upcoming road segment might form an effective roadway departure countermeasure.

4.1 Functional Goals

In order to concretely specify the actions a run-off-road countermeasure must perform in order to prevent SVRD crashes, the project team developed a set of “functional goals” in the Task 2 effort. There were six functional goals identified for an excessive speed through curve warning system.They are:

1. Monitor vehicle dynamic status to determine current vehicle speed
2. Determine geometric characteristics of upcoming road segment
3. Determine vehicle position/orientation relative to roadway
4. Detect degraded roadway conditions
5. Process data to determine acceptable speed for approaching roadway segment
6. Present phased alarm to driver of roadway departure danger due to excessive speed for approaching roadway segment

The rest of this section describes the results of experiments and analyses conducted on the first five of these functional goals, those involving the sensing and algorithm for a curve speed warning system. The sixth goal involves the driver interface, and is discussed in Volume II of this report on the Iowa driving simulator experiments.

4.2 Goal 1: Monitoring Vehicle Dynamic Status

For an excessive curve speed warning system, two important vehicle state parameters to be determined are vehicle speed and vehicle acceleration/deceleration. Both of these can be obtained from a variety of sensors in a relatively easy and cost effective manner.

4.2.1 Vehicle Velocity

Most vehicles equipped with the cruise control provide an electronic signal that represents the vehicle's speed and this signal can be integrated into a countermeasure system. Encoders mounted on an axle of the drive shaft can also be used to measure the velocity. Even though these two methods are straightforward to implement, they are affected by tire inflation pressure and temperature, and are sensitive to calibration methods used. Accuracies of better than 0.5 percent are possible, but more typical accuracies are on the order of 3-5 percent, resulting in an error of approximately l-3 mph at normal driving speeds.

A Global Positioning System (GPS) receiver can calculate the velocity based on doppler shift calculations. Most available GPS receivers provide this information. The GPS velocity estimates are more accurate than the previous methods, with an accuracy of +-0.02mph at steady rate conditions without Selective Availability (Trimble SV6 Manual). This method has the added advantage that the required GPS receiver will probably be already available, since as will be seen, it provides an effective method for estimating vehicle position for functional goal 3. It also requires no mechanical hardware or physical connections to the vehicle. However this method of speed estimation suffers from the same "dropout" problem as position estimation based on GPS. Therefore some combination of mechanical and GPS-based velocity measurement will probably provide the most accurate and reliable vehicle speed estimate.

4.2.2 Vehicle Acceleration/Deceleration

While the velocity information gives a snapshot of the vehicles's state, acceleration/deceleration estimates provide the instantaneous trend. For example, if the countermeasure system knows that the vehicle is decelerating at a rapid rate, then it can infer that the driver is attentive and that he is taking a corrective action, which in turn can be used to adjust the warning threshold.

Accurate acceleration/deceleration can be obtained either by differentiating the velocity input or by installing a low cost accelerometer.

4.2.3 Implementation and Test Results

In the curve warning system developed and tested as part of Task 3, velocity estimates are acquired from a Trimble SV6 GPS receiver. It provides velocity estimates once per second. The team conducted experiments to verify the accuracy claims for the SV6 unit. The Navlab 5 testbed vehicle was driven repeatedly over a measured mile using the cruise control to maintain a constant velocity (60 mph). The time it took to traverse this distance was measured, and the vehicle's velocity was calculated by dividing the distance by the elapsed time. The computed and GPS reported velocities were then compared. The results indicate that the GPS velocity estimate accuracy is better than one mile per hour (mean velocity error of 0.82 mph). For more details on the GPS receiver itself, see Appendix A. For more details regarding the availability of the GPS data required to estimate velocity, see Section 4.4.

4.3 Goal 2: Determine upcoming Road/Curve Geometry

Knowledge of the geometric characteristics of upcoming road segment is a prerequisite for estimating the safe vehicle speed for traversing that segment. The geometric information required includes superelevation, vertical alignment (grade) and curvature of the road segment. These can be obtained either by direct (on-the-fly) measurements, from a roadside transponder, or by extracting them from a pre-compiled map database.

4.3.1 Direct Measurement

One potential way to directly sense the upcoming road geometry is to use a vision-based system that analyses the scene ahead and extracts the necessary information. But to reliable estimate the curvature using a vision based system is very difficult because of possible occlusions and the large lookahead distances required. Also, there is no accurate way to directly sense the superelevation or vertical alignment of a road segment ahead of the vehicle.

4.3.2 Transponders

The countermeasure recommended in [15] for preventing excessive speed crashes is an infrastructure-based transponder systems. These beacons would be located at curves, and broadcast to upcoming vehicles the safe travel speed for negotiating the curve. A simple onboard system would receive this speed advisory, and sound an alarm if the driver is approaching the corner at a speed in excess of this recommendation. While potentially effective, such a system has the drawback of requiring extensive modification of the existing roadway infrastructure to deploy these beacons. From our Task 1 analysis, it is apparent that most curve related crashes occur on rural roadways, a domain in which it would be difficult to deploy and maintain the required beacons, due to the large number of roadway miles, and due to the variety of local jurisdictions with responsibility for maintaining rural roadways.

4.3.3 Commercial Map Databases

A third alternative for estimating the geometry of the upcoming road segment is to use a commercial digital map containing the required information. For example, Etak Inc. has detailed, computer readable digital maps covering the entire US. In urban areas, these maps are claimed to have +-13m accuracy from the center-line of the road. In other words, the map's reported latitude and longitude for the center of a particular intersection will be within 13m of the actual latitude and longitude (See Figure 4-1).

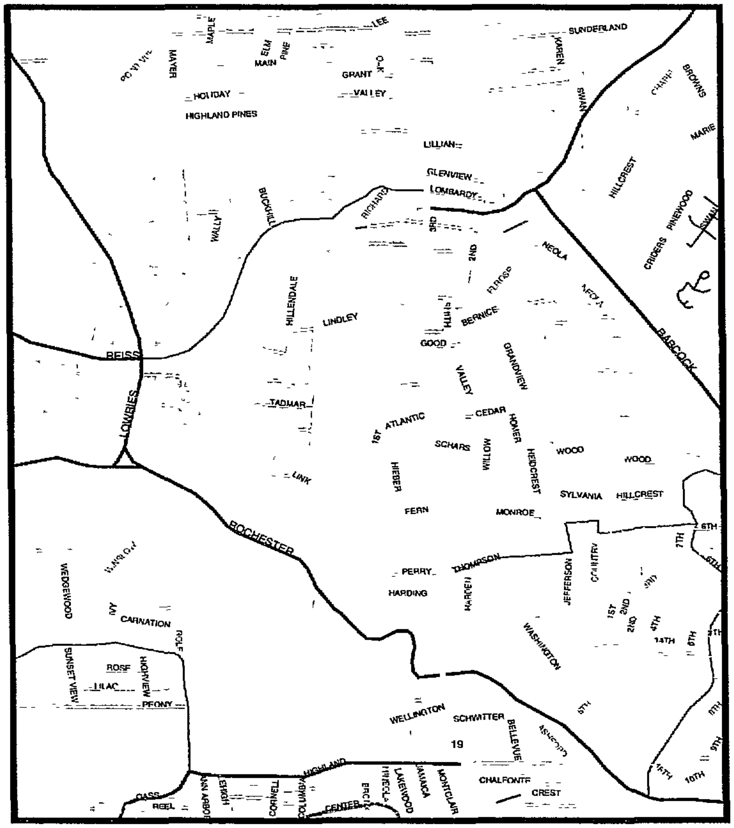

Figure 4-1: Sample Etak map data

4.3.4 Custom Built Maps

Commercial maps are digitized at a relatively coarse resolution. All the curves are represented with a series of straight line segments instead of using higher order curve segments. This is primarily done to limit the size and complexity of the database. With advances in computing, storage and representation techniques, we believe that future databases will be more accurate and will have much finer resolution.

For an excessive curve speed countermeasures system to properly estimate the safe vehicle speed, the grade and superelevation information about the road segment ahead are very important. Even though the current commercial map databases do not contain these information, it is not very difficult to collect and record the superelevation and vertical alignment data for specific road networks. This can done by installing an inexpensive roll/pitch sensor and recording the values as the data collection vehicle traverses those roads. This does require traversing each road once to collect this information. If curve warning systems were to achieve widespread deployment, it is likely that commercial map vendors would include this information in their map databases.

4.3.5 Implementation and Test Results

The project team acquired digital maps databases of several areas, including Allegheny County, PA and Washington, DC from the Etak, Inc. These databases are very large and contain much more information than it is needed for a an excessive speed through curve countermeasures system. The maps were reduced to a manageable size using scripts to extract and reformat the important information from these databases.

In addition to Etak maps, the team built custom maps of selected roads in the Pittsburgh area by driving over them once and recording the relevant information. Curve warning experiments were later done on these roads. One important. advantage of this method over using a commercial map database is that the custom maps could be built with much higher resolution than is available in the Etak maps.

The maps generated for the curve warning tests did not contain vertical alignment information. This data will be included in future experiments. Also, instead of the actual values for superelevation, these tests used estimated values. This section describes tests conducted to assess the accuracy of available digital maps.

4.351 Combining ETAK Map Database and GPS Position Estimates

As the first step towards a system for warning of excessive speed through curves, we combined the ETAK map database with the Global Positioning System (GPS) receiver into a moving map display. The display shows the test vehicle’s current location as it moves (See Figure 4-2). The red dots on the map represent the vehicle’s trajectory as estimated by the GPS system over an one mile path.

Several characteristics about the GPS performance can be noted from Figure 4-2. First, the trajectory is locally smooth, with very few discontinuities. The GPS did exhibit some dropouts, and a corresponding discontinuity in the position estimate, when driving in so-called “urban canyons” where buildings occluded the satellites. However, this is probably not a substantial problem, since the Task1 analyses for this program indicate that few roadway departure crashes occur in this type of environment.

While the local position estimates from the GPS are consistent, there remains fairly significant relative error between the GPS reported position and the map database. This error is evident in Figure 4-2 as an offset between the vehicle's path and the road being traveled. To better quantify this error, and determine whether it results from errors in the map or the vehicle position estimate, the following experiments were conducted.

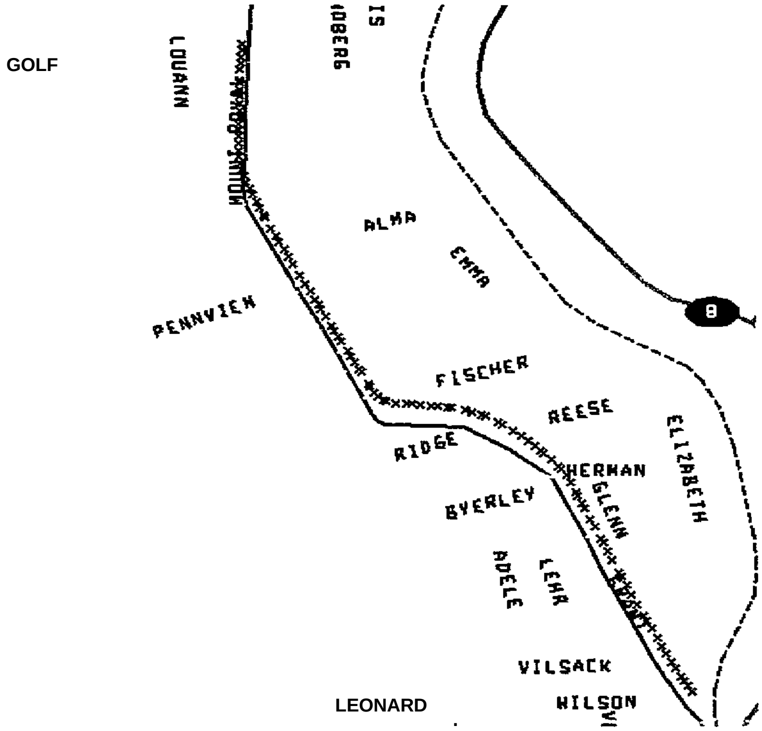

Figure 4-2: Moving map display system

4.3.5.2 Accuracy of Commercial and Custom Map Databases

We conducted a set of experiments to measure the accuracies of the Etak and custom built map databases. In these experiments, the Navlab 5 test vehicle was driven twice over a 100km route around Pittsburgh while recording the vehicle's latitude and longitude, as reported by a Trimble SV6 GPS receiver, in differential mode. The details of the differential GPS implementation and its accuracy will be discussed in Section 4.4.3. The important characteristic of the differential GPS for this experiment is that it can provide an estimate of the vehicle's latitude and longitude to within +- 6m of ground truth.

The selected route consisted of various types of roads and terrains including downtown driving with tall buildings on both sides of the road, interstate highway driving with frequent overpasses and rural driving with nearby hills and thick overhanging trees. The route followed, overlaid on the Etak map of Pittsburgh, is shown as the thick red line in Figure 4-3.

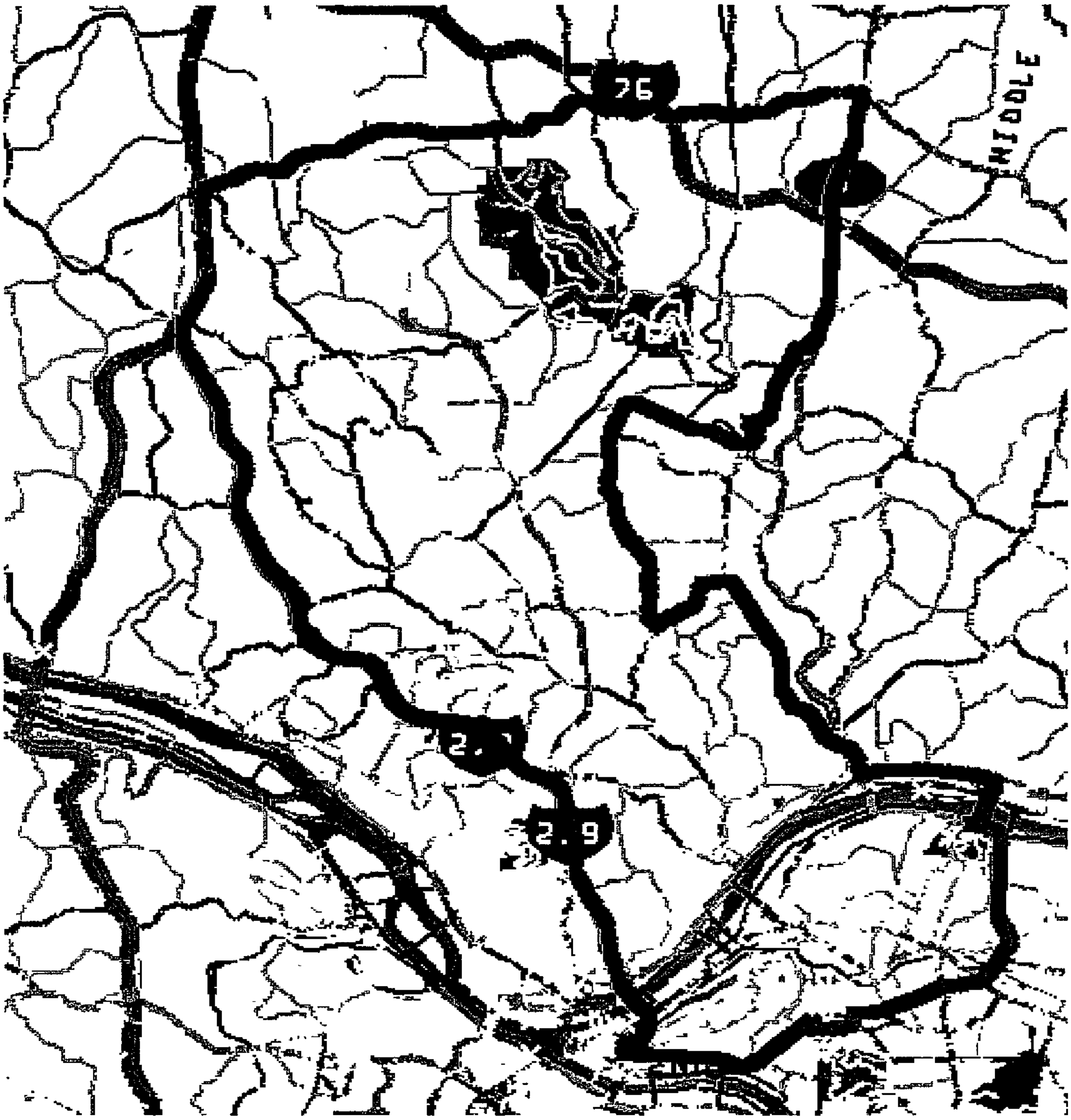

Figure 4-3: Etak map of 100 km test run

We extracted the geometric data for the corresponding roads along this route from the Etak map database and compared it with the more accurate map generated using differential GPS to determine the accuracy of the Etak map. The mean difference between the nearest road point in the Etak map and the position reported by the differential GPS during this test was 16.98m, with a standard deviation of 11.77m. As will be seen in the next section, approximately 6m of this 16.98m disagreement can be attributed to inaccuracy in the GPS position estimate. The remaining 11m discrepancy is due to inaccuracy in the Etak map. Note that these results are consistent with accuracy Etak claims for its map of +-13 meters.

A histogram representing the distribution of the discrepancies between the Etak map and the map created using differential GPS is provided in Figure 4-4. Note that the vast majority of points reported by the GPS fall within 40 meters of the corresponding point on the Etak map. There are a few points where there was a large discrepancy between the GPS data and Etak map data. Some of this discrepancy could be have been caused by the GPS receiver tracking less than four satellites and thus reporting inaccurate position data. The number of satellites tracked during the creation of the GPS map, and the effect this variability has on map accuracy will be discussed in more detail in the section 4.4.

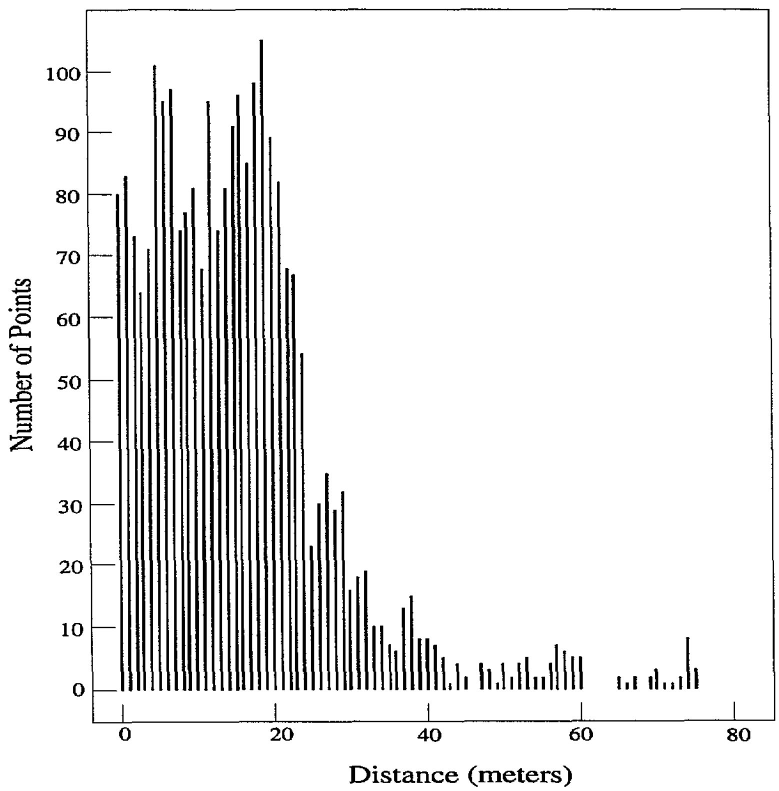

Figure 4-4: Distribution of discrepancies between Etak map and DGPS map

4.3.5.3 Curvature Estimation using the ETAK Map Database

A curve speed warning system must know the curvature of the upcoming road segment in order to calculate the safe speed. The most straightforward method for obtaining this data would be to store it in the map and read it back as the vehicle approaches a curve. Unfortunately, road curvature is not an attribute currently stored in the Etak maps. However, it is possible to compute the road curvature from an Etak map. The radius of an imaginary circle that passes through three points from the map, represents the approximate curvature of the road at the vehicle's current location. One of the three points considered is the point of projection of the current vehicle location on to the nearest Etak road segment. The other two points are located an equal distance ahead and behind the vehicle along the current road segment. For the following experiment, the distance considered was the distance the vehicle would travel in three seconds at the current velocity.

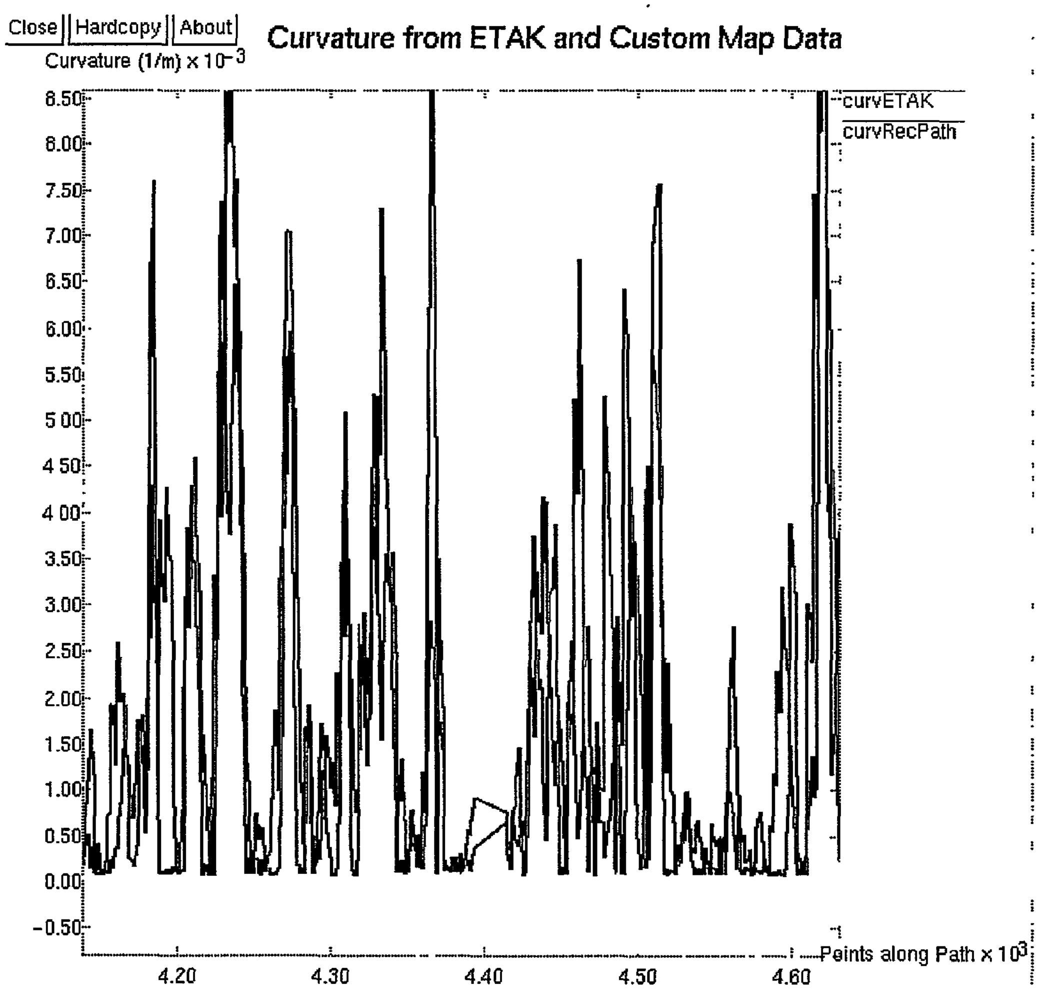

Figure 4-5: Curvature data extracted from Etak and custom map databases

To determine how accurately road curvature can be calculated from the Etak map, the project team conducted the following experiment. As the test vehicle was driven through a particular network of roads, the curvature values were estimated both from Etak map data and from a densely built custom map data with 15 meter interval between data points. Figure 4-5 shows curvature information obtained from these two sources. While they match closely in most cases, there are places where the disagreement was quite large.

Figure 4-6 shows the histogram of differences in radius of curvature obtained using the above two methods. If the radii of curvature estimated by both these methods were above 2000m, they were assumed to be in total agreement irrespective of the actual difference, since road segments with such large radius of curvature can be considered straight for purposes of a curve warning system. The curvature estimated from the Etak map data was lower than the curvature estimated from densely built custom map data in majority (67 percent) of the cases. It implies that Etak map data generally reports a shallower curve when compared to the custom map data. The mean difference in curvature obtained from these two sources was 62.27 percent, which is quite large. This can be attributed mostly to the coarseness of the Etak data although improvements in the curvature calculation technique might improve the figure somewhat.

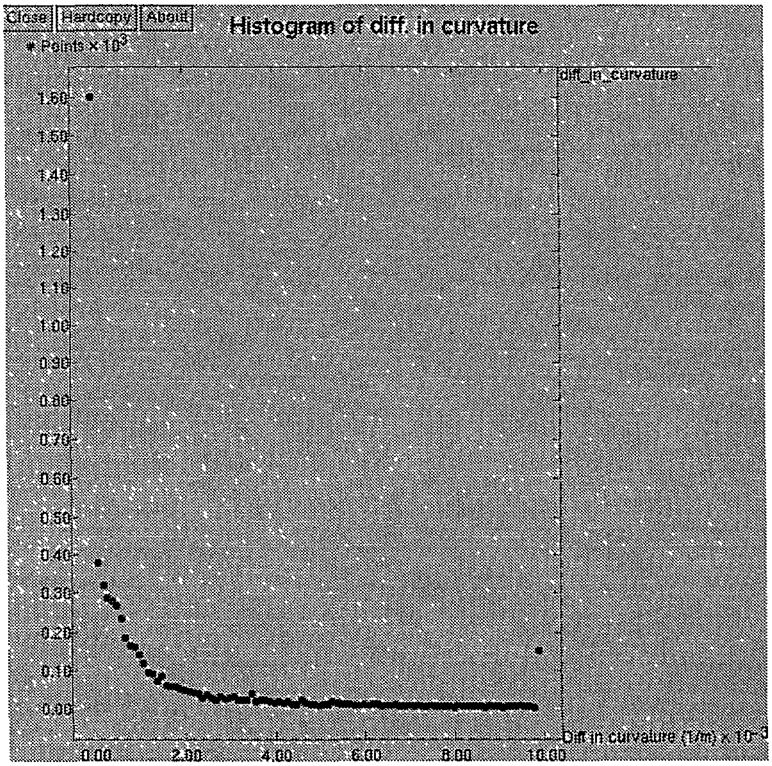

Figure 4-6: Histogram of curvature difference between Etak map and recorded map

This conclusion is supported by Figure 4-7, which shows the histogram of lengths of Etak road segments for a typical network of roads in Pittsburgh and surrounding areas. The type of roads in this sample include interstate highways, primary state highways, subsidiary state highways, arterial roads and collector roads. These segments lengths correspond to the distance between adjacent road points in the Etak map. Note that the mean distance between points is 116.4 meters and the maximum distance is over 1000 meters. This is clearly too high to support an effective longitudinal countermeasure. Further experiments need to be conducted to determine the minimum map resolution required to support a curve speed warning system.

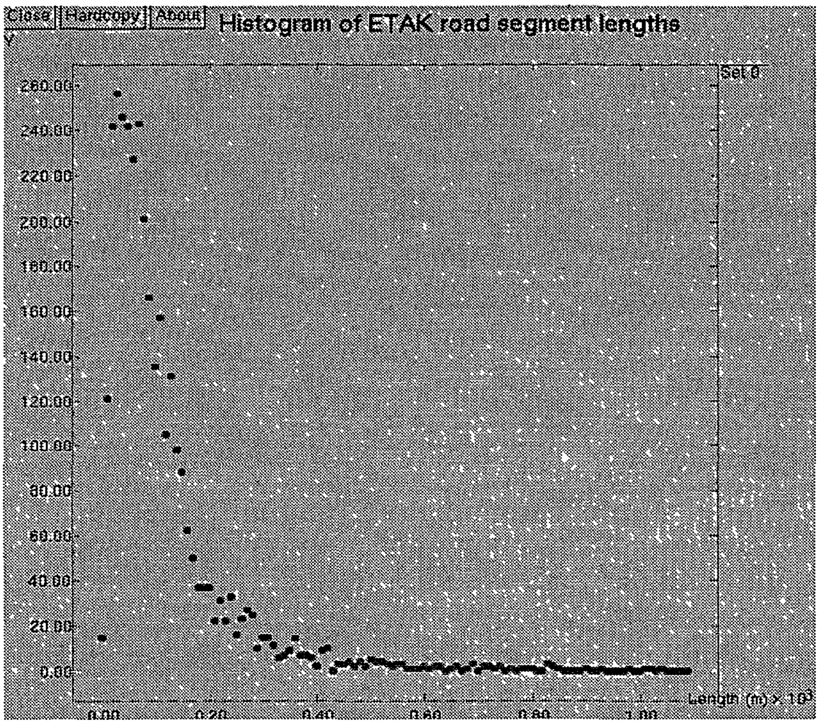

Figure 4-7: Histogram of lengths of Etak road segments

4.4 Goal 3: Determine Vehicle Longitudinal Position Relative to Curve

In order to warn or alert the driver of excessive speed at the appropriate time as he approaches a curve, a countermeasure system must accurately determine the distance to the upcoming curve. The system should also be able locate the vehicle on the correct road segment in places where there are dense network of roads and cross roads. There are several potential methods for determining the vehicle's location, each of which are discussed below.

4.4.1 Direct Measurement

One possible means for determining the vehicle's position relative to a curve is to sense it directly, for example by using a machine vision system. While theoretically possible, this approach would be extremely difficult due to the long lookahead distance required (often several hundred meters), and because the view of the curve is often obstructed during the vehicle's approach.

4.4.2 Transponders

As discussed in Section 4.3.2, transponders located at curves could be employed to broadcast information to an approaching vehicle. By measuring the strength of the signal reaching the vehicle, it should be possible to determine the distance between the vehicle and the transponder, and therefore the distance to the curve.

This approach would suffer from the same drawbacks described earlier for transponders- namely high deployment and maintenance expense. Another difficulty associated with this technique is the need for multiple transponders per curve to overcome occlusion. Finally, on particularly curvy sections of road there is the danger of interference between neighboring transponders.

4.4.3 GPS/DGPS based vehicle location

GPS (Global Positioning System) is probably the most promising technology currently available for vehicle position estimation. There is strong commercial interest in this area and many organizations are involved in active research perfecting this technology. While there are some potential problems with GPS, like dropouts due to satellite occlusion, considerable effort is currently underway to increase the utility of GPS for various ITS applications. Advances being made in disciplines such as aviation and surveying are also advancing the state-of-the-art in GPS technology. The next section presents a brief overview of the GPS technology and its capabilities.

4.4.3.1 GPS Technology

GPS is a global, all weather, 24-hour, satellite-based navigation system. At the heart of GPS are the 21 satellites placed in circular orbits at an altitude of 20,200 km. Each satellite broadcasts a signal which encoding its positions along with other information such as its orbital data, clock synchronization correction and status information. A GPS receiver on the ground uses the passive ranging concept called pseudoranging to calculate its position and velocity. The receiver acquires the satellite signals and measures pseudoranges to the satellites. From this pseudorange information, it can determine its position by converting the ranges to a point through triangulation. Positional accuracy of between 10 cm to 100 meter is attainable, depending on the type of receiver used, antenna dynamics, the mode of operation and the processing techniques employed by the receiver.

The accuracy of single GPS receiver is affected by errors from various sources. Examples include:

- Satellite orbit error
- Satellite clock error
- Signal path error - Ionosphere
- Signal path error - Trophosphere
- Receiver multipath error
- Receiver delay error
- Selective availability (intentional degradation of signals by DoD) etc.,

Because of these error sources, the positional accuracy of a typical commercial grade GPS receiver is on the order of 50- 100 meters.

With this level of accuracy, there is a significant potential for false alarms from a curve warning system. This could occur when the countermeasure underestimates the distance to the upcoming curve, and falsely concludes the vehicle is travelling too fast. There is also the danger of missed alarms, when the system overestimates the distance to the upcoming curve, and mistakenly judges the vehicle's current speed to be safe.

4.4.3.2 DGPS Technology

To improve the accuracy of GPS, the technique of differential GPS has been developed. Differential GPS is based on the principle that any two receivers in the same general region of the Earth's surface will make approximately the same errors in measuring satellite signals, since they share the same major sources of error. These errors can be compensated for by placing a "reference" receiver at a fixed, surveyed location and measuring the aggregate effect of these errors. When this aggregate error information is provided to a mobile receiver, the mobile receiver can refine its position estimate, significantly improving its accuracy.

4.4.3.3 Current and Expected GPS Capabilities and Performance

The report on Carrier Phase GPS prepared by SRI International for FHWA [33] presents a good summary of the state-of-the-art in GPS technology and its trends. Table 4-5 summarizes the information in that report regarding the current and anticipated capabilities of GPS technology. As can be seen from the table, substantial improvements in both price and performance of GPS receivers are expected, making GPS a promising technology for ITS applications.

Table 4-5: Current and anticipated capabilities of GPS receivers

	CURRENT	ANTICIPATED
Positional Accuracy with DGPS – Code	1m	0.5m
Positional Accuracy with DGPS – Carrier	1-10 cm	1-5 cm
Velocity Accuracy with DGPS	0.02 m/s	0.01 m/s
Attitude Accuracy (1-m antenna spacing)	0.1 deg	0.1 deg
Update Rate	1-10 hz	50-100 Hz with Inertial Ref Unit
Size	2.5-3.00 in^3	1-10 in^3
Cost	$150-$35,000	$75-$1000

4.4.3.4 Implementation and Test Results

In order to evaluate the performance of currently available commercial grade GPS receivers, we acquired and equipped our testbed vehicle, Navlab 5, with a low cost ($600) Trimble SV6 GPS [35]. It is a six channel receiver with capability to track up to 8 satellites. The positional accuracy is specified as 25-100 m without DGPS and better than 10 m with DGPS. The SV6 also provides an estimate of velocity, with a claimed accuracy of 0.02 m/s with DGPS. It has an update rate of 1 HZ.

We conducted a series of experiments to test this GPS system.The first of these experiments was designed to measure the steady state accuracy of the GPS system without differential correction. In this experiment, the receiver was placed in a fixed location and the position data was collected over a 12 hour period. There was no differential (DGPS) input to the receiver. The largest excursion during the 12 hour period was approximately 45m (see Figure 4-8), supporting the manufacturers claim of 20-1OOm accuracy.

While these results were encouraging, this level of accuracy is too low to effectively support a curve warning system. A 45m error in a countermeasure's estimate of the distance to an upcoming curve would result in a two second error in warning onset time if the vehicle is traveling at 50 mph A warning two seconds early would almost certainly be perceived by the driver as a false alarm. A warning two seconds late would probably not allow the driver sufficient time to decelerate the vehicle to a safe speed before entering the curve.

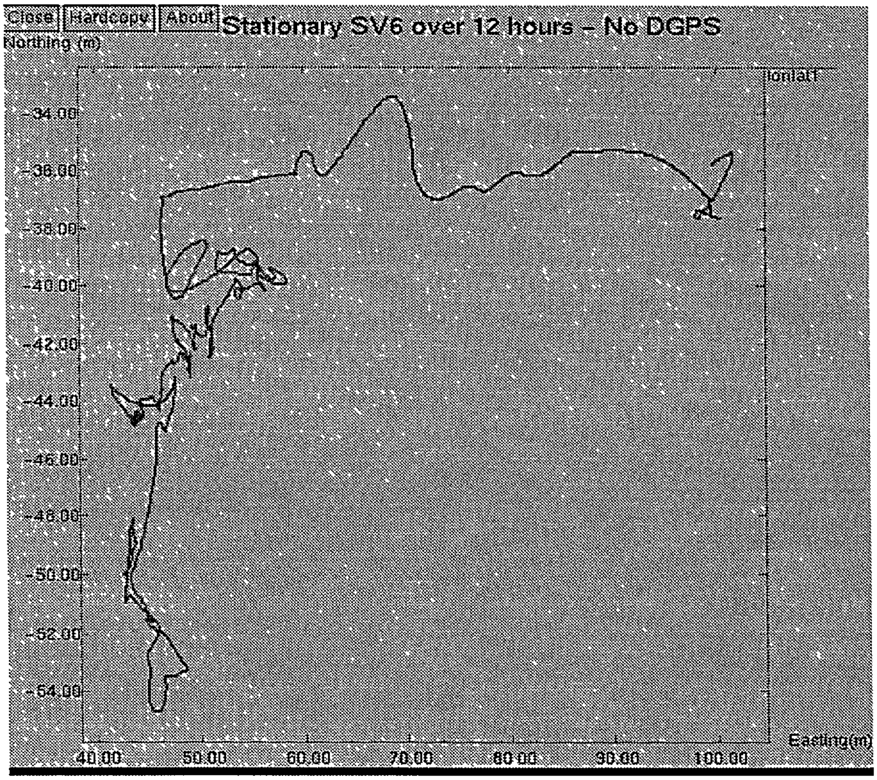

Figure 4-8: Position estimates from stationary GPS receiver

4.4.3.5 Differential GPS Tests

In order to overcome the problem of position estimation error inherent in stand-alone GPS receivers, we tested the Trimble SV6 GPS receiver with differential GPS input from two different systems: Omnistar and Navstar. These two DGPS systems differ significantly both in processing techniques and implementation.

4.4.3.5.1 Stationary Omnistar DGPS Tests

The Omnistar system is a nationwide differential GPS broadcast system commercially available from John E. Chance & Associates. It has ten base stations located throughout the US and these stations provide the differential corrections. The corrections are uplinked to a satellite and broadcast back to earth-based downconverter systems, which reformat the data and supply differential corrections in a format readily accepted by most GPS receivers, including the Trimble SV6.

Figure 4-9 shows the performance of the SV6 with DGPS corrections from the Omnistar system while the vehicle was stationary over a 7 hour period. The accuracy is on the order of +-4m. Though these tests showed the Omnistar to be a convenient and accurate source of DGPS corrections, there were several problems with the system. First, the Omnistar's performance was significantly degraded in urban areas, where the visibility of the Omnistar satellite was occluded by buildings. Also, the Omnistar system is currently quite expensive, $6000 initial cost plus $4000 per year. The primary advantage of the Omnistar is that the hardware configuration is very convenient. The unit is simply mounted on the exterior of the vehicle, and connected directly to the GPS receiver. Unlike the Navstar system to be described next, the Omnistar does not require a direct communication link between the basestation and the mobile receiver, since the differential corrections come directly from an additional satellite.

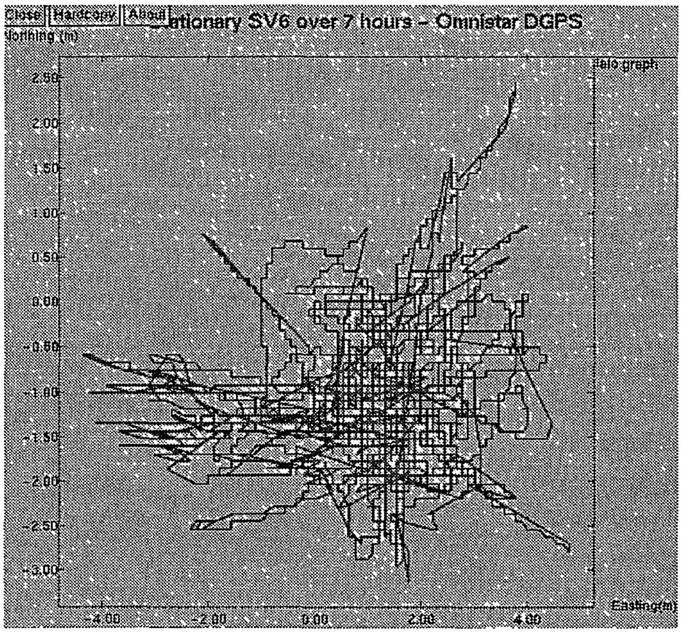

Figure 4-9: Position estimates from stationary GPS receiver with Omnistar DGPS

4.4.3.5.2 Stationary Navstar DGPS Tests

We also acquired a $3000 Navstat-XR5M GPS receiver system with differential output capability and used it as a differential basestation. The team mounted the basestation receiver on the roof of a Carnegie Mellon building at a surveyed location. Communication between the basestation and the SV6 receiver on the Navlab 5 test vehicle was established using a cellular phone and modem. Figure 4-10 shows the performance of SV6 with DGPS corrections from the Navstar unit over a one hour period while the vehicle was stationary. Its accuracy (+- 3 meters) appears to be slightly better than the Omnistar system.

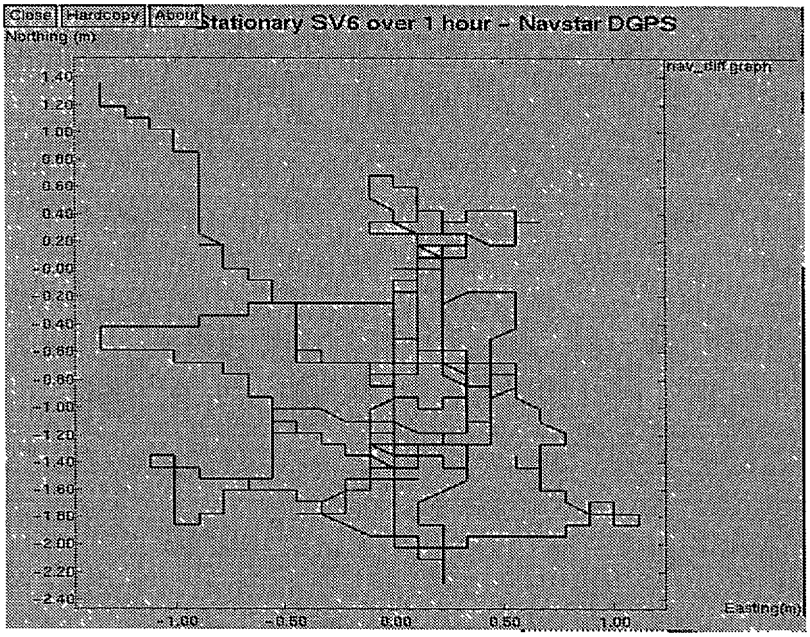

Figure 4-10: Position estimates from stationary GPS receiver with Navstar DGPS

4.4.3.5.3 Broadcasting DGPS over FM Subcarrier

The DCI Inc. (Differential Corrections Inc.) broadcasts differential signals through the FM Sub-Carrier of the commercial FM radio broadcasts. At this time, this method appears to be the least expensive way to receive DGPS signals, at $200-400 per year. This service is currently available from DCI in over 50 cities around the country. Unfortunately, Pittsburgh is not one of them. Over several months of negotiations with DCI and a local radio station, the project team attempted to bring this service to Pittsburgh. This would have provided DGPS signals that could improve the accuracy of the Trimble GPS system to the range of l-5m, according to specifications provided by DCI. Unfortunately, for commercial reasons these efforts did not succeed in bringing this service to Pittsburgh, so this source of differential GPS corrections was not tested.

4.4.3.5.4 Tests with Long Baseline DGPS

One potential problem with differential GPS is that the greater the distance between the basestation receiver and the mobile receiver, the more the important factors affecting error in the two receivers differ. This should result in degraded position estimation accuracy. In order to test this effect, a set of experiments was conducted to evaluate the performance of differential GPS with a very long baseline between the vehicle and the basestation.

Specifically, the testbed vehicle was driven around the 7.5 mile oval test track at the Vehicle Research and Test Center (VRTC) in East Liberty, Ohio while the Trimble SV6 GPS unit received differential corrections from the Navstar basestation in Pittsburgh. The distance between the base station and the mobile receiver was over 200 miles in this test. There appeared to be no significant degradation in GPS accuracy under these conditions with an apparent mean error of less that 5 meters (See Figures 4-11 and 4-12). This was somewhat of a surprising result, since it was expected that differences in atmospheric conditions, and differences in the visible satellites between the base station and the mobile unit would result in degraded performance. This results supports the viability of a curve warning countermeasure, since it suggests that sufficient position accuracy can be achieved without heavy reliance on the infrastructure in the form of closely spaced differential basestations or roadside transponders.

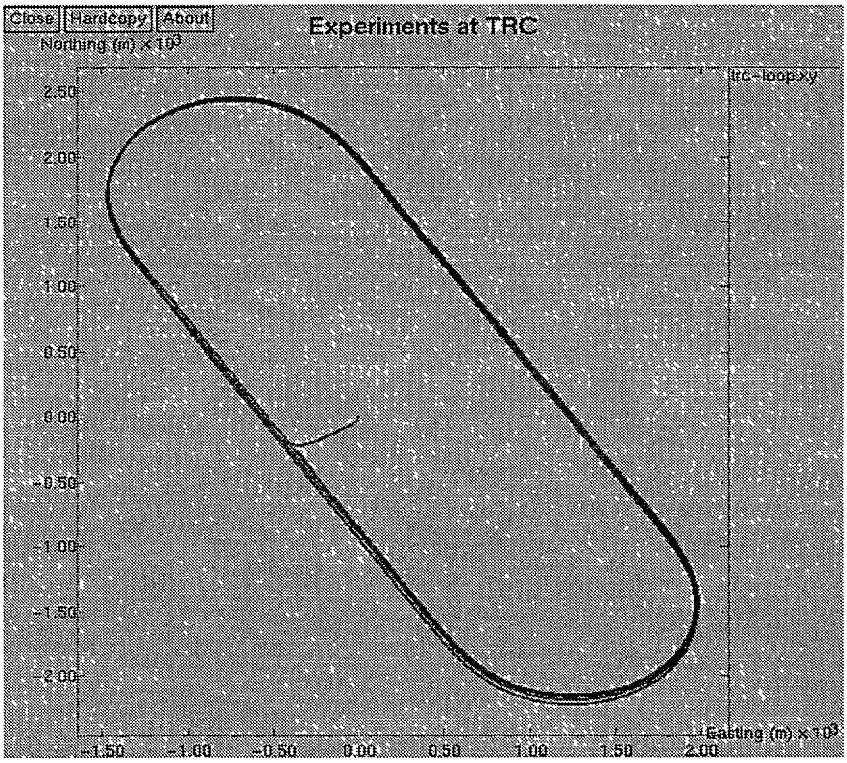

Figure 4-11: Data from long baseline DGPS test

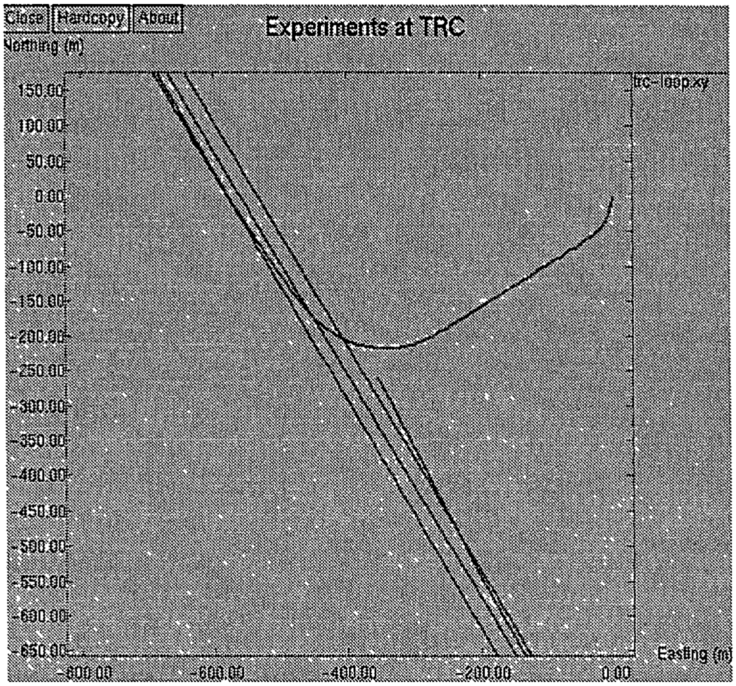

Figure 4-12: Detailed data from long baseline DGPS test

4.4.3.6 GPS Latency Tests

Another potential problem, particularly with inexpensive GPS receivers, is latency. With differential corrections, these receivers can accurately estimate the vehicle's location, but because of processing delays this estimate actually corresponds to the vehicle's location up to several seconds earlier. As a result, the vehicle may be significantly closer to the upcoming curve than is indicated by the GPS, possibly resulting in a warning too late for the driver to respond. In order to quantify the latency in the Trimble SV6 GPS receiver with differential corrections from the Navstar, we conducted the following experiment.

The Navlab 5 testbed vehicle was repeatedly driven in both directions along a straight stretch of road at a constant speed of 45 mph. Each time the vehicle passed a particular point (plotted as point [O,O] in Figure 4-13) the GPS estimate of vehicle position was recorded. As can be seen from Figure 4-13, the GPS position estimate lagged behind the vehicle's actual position by 20 to 40m. This corresponds to a 1 to 2 second latency, since the vehicle was traveling at 20 m/sec (45 mph).

It is important to note however, that this latency appears to be quite regular and predictable. This regularity allowed the curve warning countermeasure developed for this task to compensate for the latency by simply assuming that the vehicle is actually 1.5 seconds closer to the upcoming curve than is reported by the GPS system. In higher quality GPS receivers currently available (and in future inexpensive GPS receivers) this latency problem should not be an issue, since these systems process faster, reducing the latency, and provide a timestamp with each position estimate, allowing a countermeasure to precisely determine the vehicle's current position.

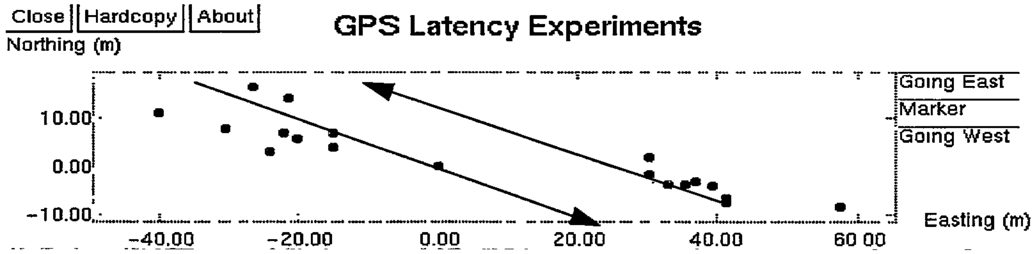

Figure 4-13: Data from GPS latency experiment

4.4.3.7 Tests of GPS Satellite Tracking Performance

A third problem commonly attributed to GPS is the difficulty these systems have in accurately estimating vehicle position when view of the satellites is occluded by buildings, overpasses, nearby hills or overhanging trees. The project team conducted several experiments to quantify the effects of reduced visibility to the GPS satellites.

The first test was to determine how much of an impact various visual occlusions have on the ability of GPS receivers to track satellites. This test involved driving the Navlab 5 test vehicle twice over the same 100km route through urban, suburban and rural areas depicted in Figure 4-3 over the period of several days. During each traversal, the number of satellites being tracked by the GPS was recorded. Results from these tests are provided in Table 4-6. As can be seen from this table, satellite tracking was quite reliable with the Trimble SV-6 GPS. Over both traversals, the GPS was unable to track 3 or more satellites less than 0.2 percent of the time. Some of this "drop-out" occurred when driving through downtown Pittsburgh, and some of it occurred when traveling along rural roads with extremely dense overhanging trees. For more than 99.8 percent of two trips, the GPS maintained lock on a sufficient number of satellites to allow it to provide an estimate the vehicle's position. The accuracy of these estimates are discussed in the next section.

Table 4-6: GPS satellites tracking statistics

Satellites Being Tracked	6	5	4	3	< 3
Run 1 (percent)	45.8	31.9	18.6	3.4	0.2
Run 2 (percent)	14.5	55.3	23.8	6.3	0.1

4.4.3.8 Extended Tests of GPS Accuracy

The final set of tests involved quantifying the accuracy of differential GPS when driving in naturalistic environments. The same 100km test route was traversed twice over several days. During each traversal the latitude and longitude reported by the SV6 with Navstar differential corrections was recorded at one second intervals. The estimated position of the vehicle at each point along the route was compared between the two traversals, to determine the consistency of the DGPS position estimates. The distribution of the discrepancies between the position estimates during the two traversals is plotted as a histogram in Figure 4- 14.

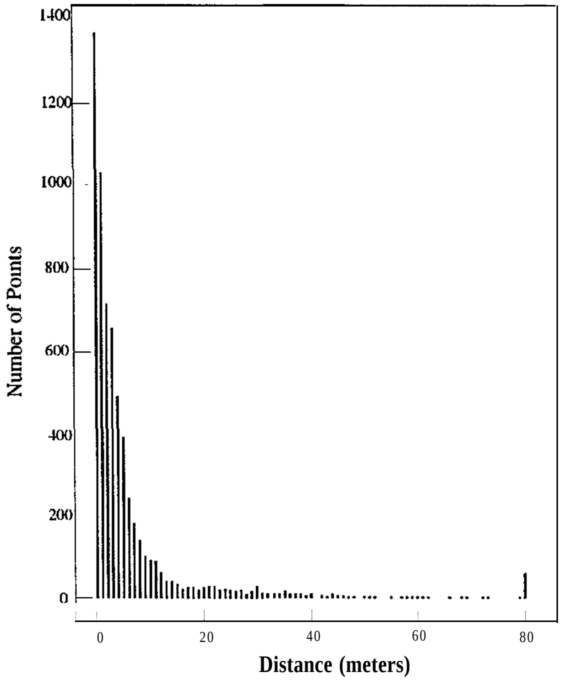

Figure 4-14: Histogram of difference between curvatures from Etak recorded maps

The histogram shows that for an overwhelming majority of the two runs, the two vehicle paths reported by the GPS were within 10-15m of each other. The mean discrepancy between the position estimates on the two traversals was 6.24m, with a standard deviation of 11.05m. This results supports the manufacturer's claim that with the SV6 is able to achieve 10m accuracy when coupled with differential corrections. Note that this level of agreement between two recorded paths does not prove that the SV6 was providing accurate ground truth estimates of latitude and longitude, since there could be a consistent offset in the system. However for a curve warning system, absolute accuracy is not particularly important. What is important is the repeatability of the position estimates over time, and for this purpose comparing two paths recorded over several days is an appropriate test.

As the histogram in Figure 4-14 indicates, there were a few large discrepancies between the position estimates during the two traversals, represented by the spike at 80m (the maximum error allowed). These were primarily caused by large jumps in the GPS position estimate when driving in downtown Pittsburgh. The problems GPS have in these so called "urban canyons" is depicted in the Figure 4-15. It shows a close-up of the two recorded paths while the vehicle traveled through downtown Pittsburgh. There were several large jumps in the position reported by the GPS, corresponding to times when there were not enough satellites visible to get an accurate estimate. Fortunately, the Task 1 analysis conducted for this program indicates that few roadway departure crashes occur in this type of extremely built up environment. On more typical stretches of suburban and rural roadways, The GPS position estimates were quite consistent between the two runs, as is visible in Figures 4- 16 through 4- 19. Figures 4-20 and 4-2 1 show repeated traversals of a three mile loop of interstate highway between two exits. Note that it is possible to determine which side of the divided highway the vehicle is traveling along from the GPS position data.

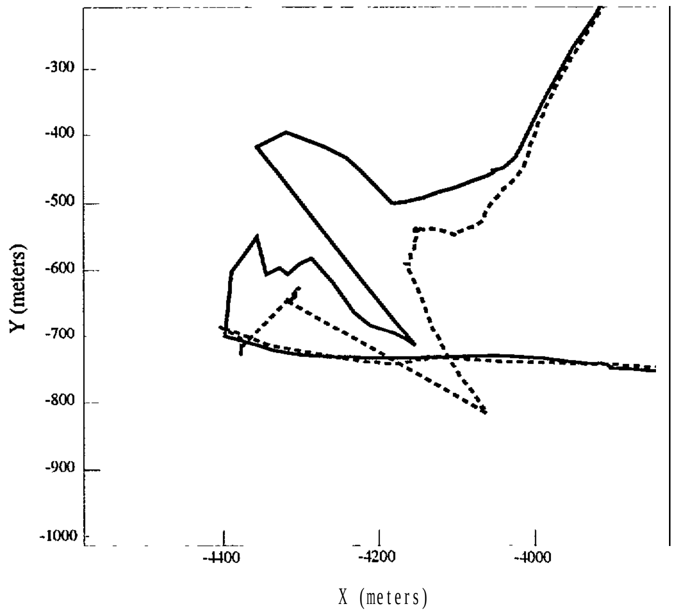

Figure 4-15: Position data near downtown area

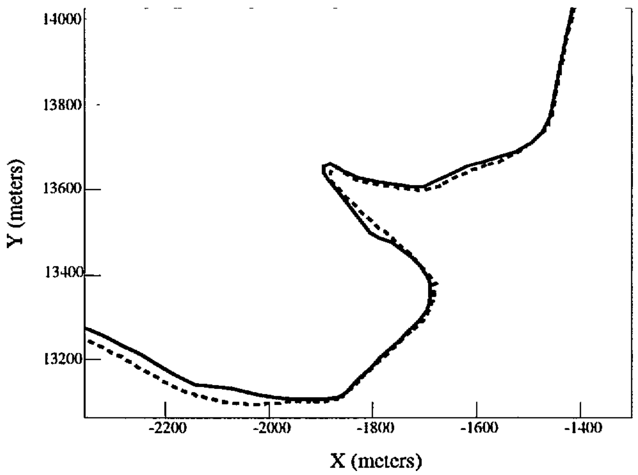

Figure 4-16: Position data near a sharp curve

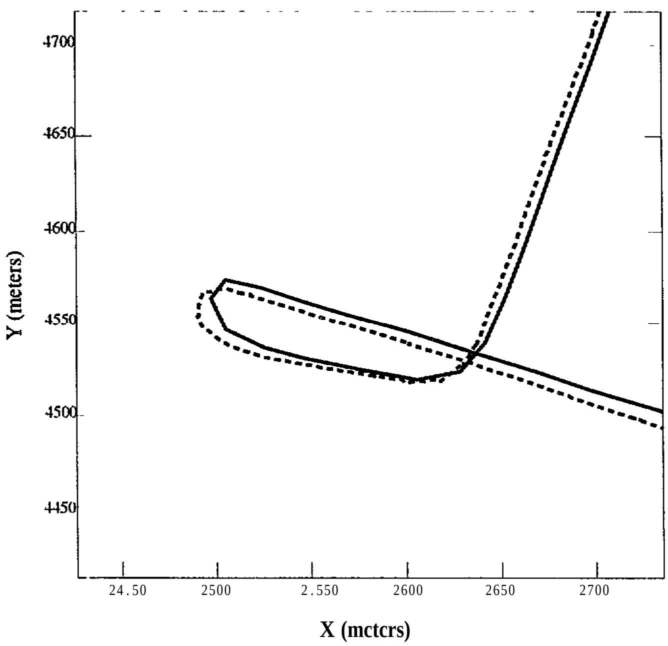

Figure 4-17: Position data near a cloverleaf

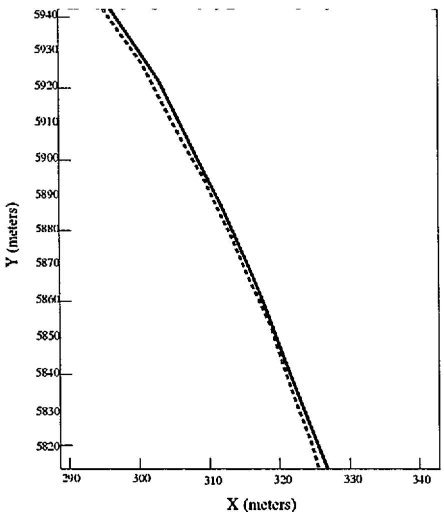

Figure 4-18: Position data on a straight road segment

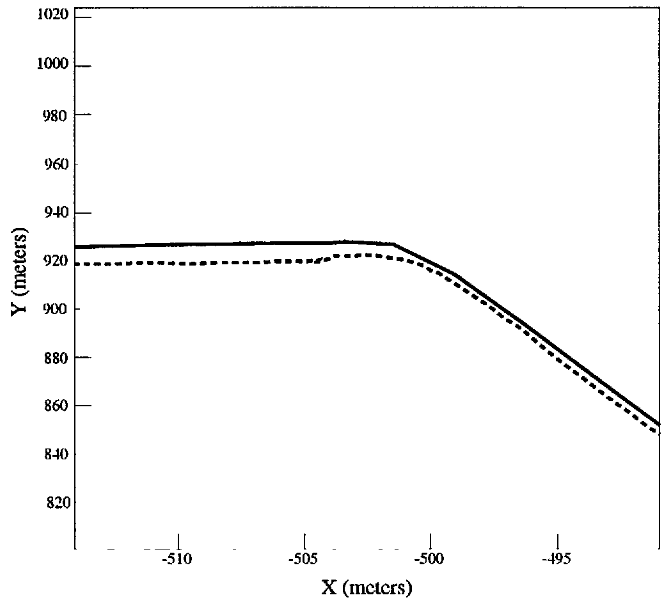

Figure 4-19: Position data near a shallow curve

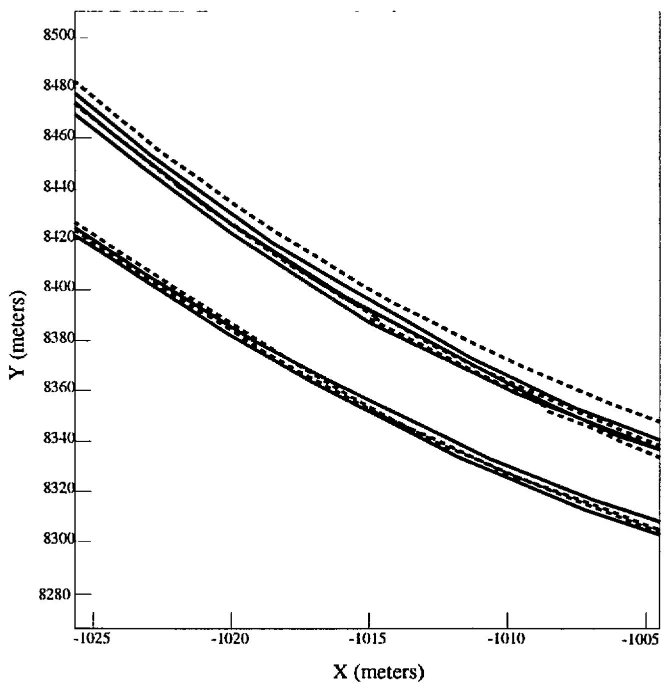

Figure 4-20: Data collected during repeated traversals of a divided highway

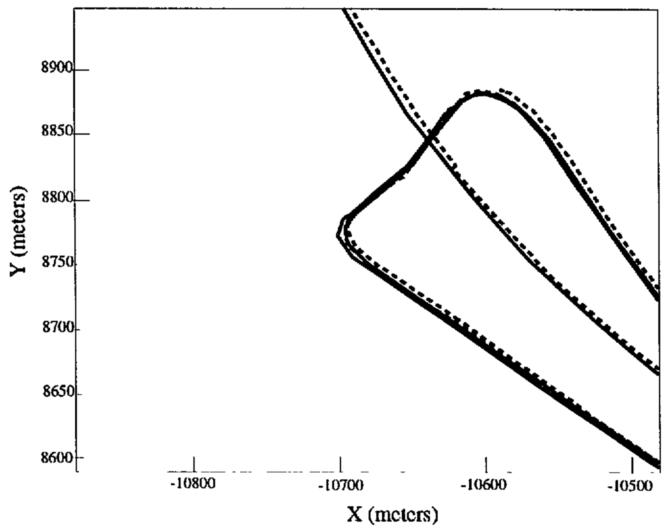

Figure 4-21: Data collected during repeated U-turns at divided highway exit

4.4.4 Implications of Results

The implications of the preceding experiments for a curve warning system are significant. They suggest that a countermeasure with a differential GPS and a digital map should be capable of accurately determining both the distance to and severity of an upcoming curve. At 50 mph, the variability in warning onset time due to inaccuracies of the GPS and map would be in approximately 0.5 seconds given an accurate manually recorded map, or +-1.25 seconds given a map with the accuracy of the Etak one tested. The variability in the former condition would probably not even be noticed by the driver, and could certainly be compensated for using a slightly earlier warning onset to ensure the driver has sufficient time to slow the vehicle before entering the curve. The +-1.25 sec. variability when using commercially available maps could potentially cause driver acceptance/performance problems, particularly if coupled with the uncertainty in road curvature reported earlier when using Etak maps. A warning triggered one second earlier than is required due to inaccuracies in the countermeasures estimate of position or road curvature could potentially annoy the driver, and a warning triggered one second late could potentially leave the driver insufficient time to slow the vehicle before entering the curve. In the Task 4 mathematical modeling effort, the potential impact of these inaccuracies will be investigated analytically.

4.5 Goal 4: Detect Degraded Roadway Conditions

The Task 1 analysis conducted for this program indicates that degraded pavement conditions in the form of water, snow or ice are present in 35.5 percent of roadway departure crashes (Source: 1992 GES). The clinical analysis conducted for Task 1 indicates that degraded pavement conditions are an important causal factor in 16.0 percent of all run-off-road crashes. Thus degraded roadway conditions play an important role in roadway departure crashes. In particular, the physical condition of the roadway surface is an important factor determining the safe travel speed for negotiating a curve. The influence of degraded conditions can be divided into two components:

- Conditions that are inherent to the physical pavement itself. Examples include roadway microstructure, roadway macrostructure, potholes, shoulder, roadway markings etc.
- Transient conditions such as rain, snow, ice or oil on the pavement

These roadway surface conditions affect the controllability of the vehicle by influencing the lateral and longitudinal coefficient of friction between the vehicle's tires and the pavement. To effectively use this information in a SVRD type countermeasures system, a countermeasure not only needs to sense these conditions, but also to translate the acquired information into an estimate of the safe travel speed. The team's investigation of this area indicates no commercially available systems exists that can readily perform both these functions. The available research literature on this area is still very preliminary, and therefore no complete system was identified or acquired for testing in this effort. However individual components which might eventually be part of a system for real-time detection of degraded pavement conditions have been identified and investigated as part of the Task 3 effort. The results of these activities are described below.

4.5.1 Infrastructure-Based Sensing of Roadway Conditions

Technology for roadway condition monitoring can be divided into two categories, infrastructure-based and vehicle-based. Several infrastructure-based systems are commercially available. These system are primarily used to determine when conditions warrant salting or plowing roads and airport runways during the winter. An example of this type of system is the SCAN system manufactured by Surface Systems Incorporated. The SCAN system includes sensors mounted below ground, on the pavement surface and above the ground. The SCAN system provides the following information:

- Air temperature, dewpoint temperature
- Surface temperature, Subsurface temperature
- Humidity
- Concentration of chemicals on the road
- Type (ice, snow, rain) and amount of precipitation on the road
- Visibility
- Wind direction and velocity

The SCAN system not only gives an instant readouts of these values, but also maintain a history of the temperature profiles. This information is useful for predicting adverse pavement conditions well before they occur,

The project team arranged with the PA Department of Transportation, a local user of the SCAN system, to access the data provided by one of their sensor stations. The project team downloaded the data from one station for the month of January 94 (See Figure 4-22).

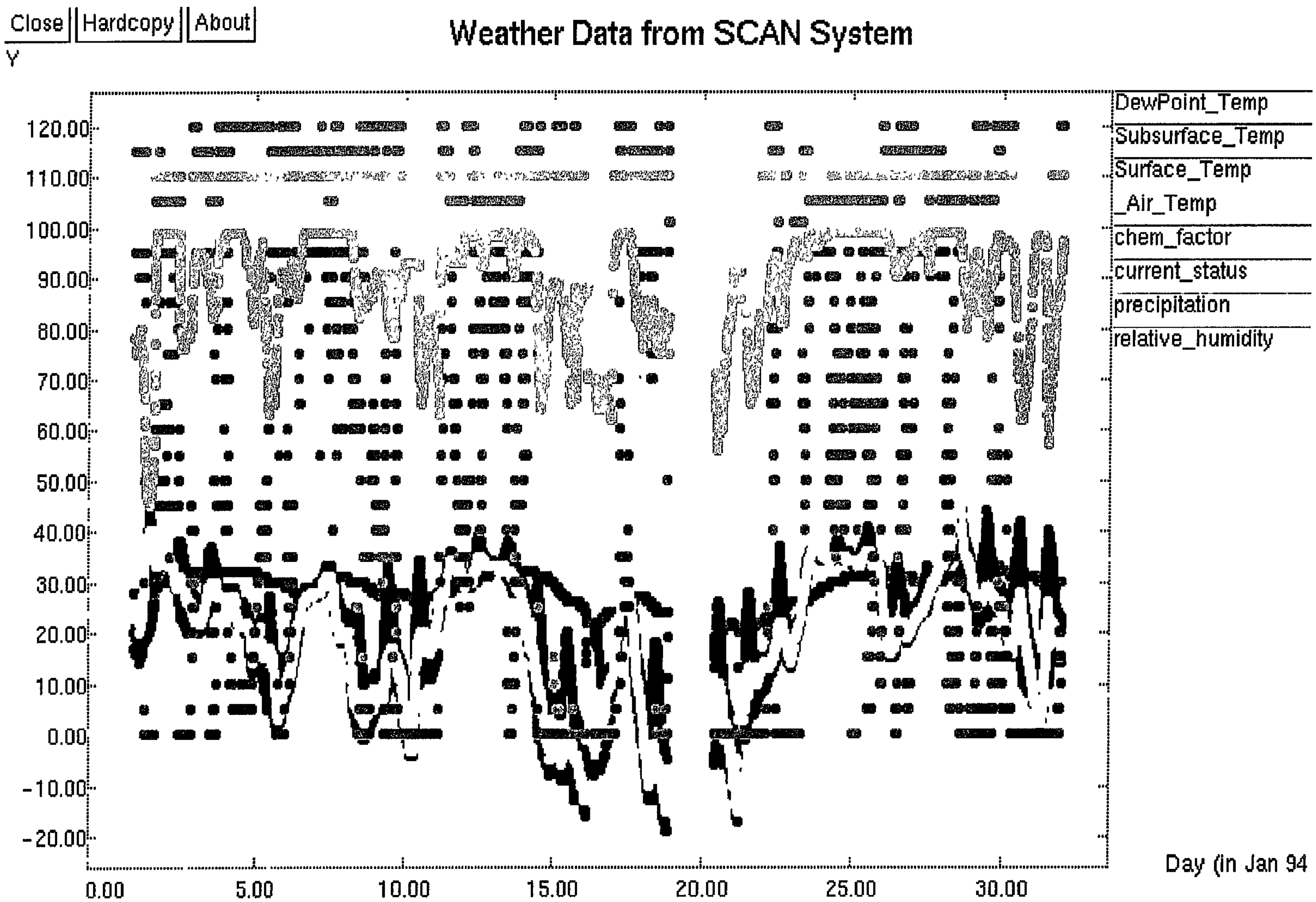

Figure 4-22: Data from the SCAN pavement monitoring system

The data includes 8 different variables, recorded every 15 minutes at a monitoring station located on interstate I-79 north of Pittsburgh. The first variable is the “status”, which indicates the type and amount of precipitation on the roadway. There are three variables indicating the temperature of the air, pavement surface, and ground below the pavement. There are also variables indicating the concentration of chemicals on the pavement, the dew point, and the relative humidity.

Clearly, the SCAN system can provide much useful data regarding the current weather and pavement conditions. The remaining question is how to convert this data into a warning signal that would be useful and easy for the driver to interpret. Surface Systems Inc. offers a service called SCAN*CAST in conjunction with their sensor systems. SCAN*CAST is a forecasting facility specializing in the prediction of pavement conditions. Staffed by professional meteorologists, SCAN*CAST issues 24-hr pavement advisories based on data collected from on-site sensors in addition to information provided by the National Weather Service. Unfortunately, tests of this service as part of Task 3 were thwarted by the unusually mild winter of 1994-95. The project team recommends further experiments be conducted in Phase II and/or III to determine the timeliness and reliability of these predictions.

One advantage of infrastructure-based pavement condition monitoring systems over in-vehicle systems (discussed below) is that they can provide advanced warning of slippery pavement, before the vehicle actually encounters it. The disadvantage is that the information they provide is very localized, For instance, PennDOT currently has only eight SCAN sensor packages in Western Pennsylvania. They are far to scattered too provide effective coverage. In particular, with this type of distributed sensor deployment it is nearly impossible to detect localized conditions, such as patches of ice, which often lead to roadway departure crashes. At approximately $35,000 per remote sensing station, it is unlikely that dense coverage will be achieved with this type of system anytime soon.

4.5.2 In-Vehicle Sensing of Roadway Conditions

An alternative approach to the detection of degraded pavement conditions are in-vehicle sensors. Though there are several in-vehicle based prototype weather sensors that currently exist, most of them are either still in the research stage or have limited functionality. None of them are commercially available.

Researchers at Mercedes-Benz in Germany have used a microphone mounted in the wheel well of an automobile and analyzed the audio signals to determine if the pavement is wet [11]. They were also able to determine the depth of water by classifying these signals. The IDEAS program of the Transportation Research Board and the US Department of Transportation have sponsored several research projects to build sensors that can detect ice crystals [3]. The European DRIVE project has developed non-contact sensors based on microwave, laser and infrared-based technologies to measure wet and icy conditions [7]. These systems are still experimental, and the data they provide must still be interpreted to determine the effect the degraded pavement conditions may have on the safe travel speed. As is explained below, this interpretation is often extremely difficult.

4.5.3 Determining the Coefficient of Friction

Degraded pavement conditions influence the safe travel speed through their impact on the coefficient of friction between the tire and the roadway. The coefficient of friction also varies with a number of other factors, including:

- Vehicle speed
- Road surface macro and microstructure
- Tire pressure
- Tread depth and configuration

The information available in the technical literature about how to determine the coefficient of friction from these parameters is very sparse and inconsistent. The American Association of State Highway and Transportation Organizations (AASHTO) recommends that when designing roadways, the assumed side friction factors should be in range of 0.1 (at 70mph) to 0.17 (at 2Omph). The design of curves as proposed by the AASHTO policy is based on the assumptions that the curve is properly spiraled, and that the vehicle tracks the curve as it is designed. Research suggests both of these assumptions are often invalid [1][2][9]. On older stretch of road, curves are frequently unspiraled. Also, aggressive drivers tend to track unspiraled curves in a manner that produces significantly greater friction demands on the tire/roadway interface than are intended by the AASHTO design policy.

At the same time there is evidence that the AASHTO standards may be overly conservative. Data from a study sponsored by the European Organization for Economic Cooperation and Development [28] on the effects of tire tread and water on the roadway is shown in Table 4-7. The data shows that available lateral friction varies tremendously with both tire condition and the amount of precipitation on the roadway.

Table 4-7: Lateral friction coefficient for various road/tire conditions

Lateral coefficient of friction	Dry conditions	Wet conditions		
		20 mph	40 mph	60 mph
Tire with full tread	0.9 .	0.8	0.55-0.68	0.20-0.60
Smooth tire	0.9	0.6	0.35-0.50	0.15-0.35

The above data indicates that it may be very difficult to convert the values of important secondary factors such as pavement conditions into a coefficient of friction. An alternative approach is to infer the coefficient of friction directly by observing the dynamic behavior of the vehicle. Ray [29] has shown through simulations that the coefficient of friction can be determined in real time using sensors that could reasonably be mounted on a vehicle. Under most conditions, if the vehicle is maneuvering, the coefficient of friction can be estimated to +-0.05 of the actual value. Briefly, the procedure is to measure tire angles and vehicle accelerations and use a simplified vehicle model to infer the tire forces. Then the most likely coefficient of friction is estimated. Of course, this technique provides an estimate of the friction coefficient at the tires' current location, and it is not necessarily a precise indicator of the friction on upcoming road segments.

While still experimental, this approach to directly estimating the coefficient of friction from vehicle dynamic behavior shows promise. The major drawback of this approach for a curve warning countermeasure is that it requires the vehicle to actually encounter the slippery stretch of pavement before the danger can be detected. For a curve warning system, by the time the vehicle reaches the slippery pavement, it may be too late for the driver to decelerate sufficiently to avoid a roadway departure. An alternative would be to communicate the coefficient of friction from vehicles which had previously traversed a section of roadway to vehicle's approaching the section. A practical means for communicating this information remains to be worked out.

4.5.4 Implementation and Testing

For the integrated countermeasure tests described in Section 4.8, the problem of automatically detecting degraded roadway conditions was circumvented by manually providing the system with a approximate estimate of current coefficient of friction, based on Table 4-7. Specifically, for tests conducted under wet roadway conditions, the coefficient of friction was set to 0.3, and for dry conditions it was set to 0.4-0.6. Clearly further research is required, either as part of this program or another, to identify and evaluate the most appropriate method for detecting reduced coefficient of friction situations.

4.6 Goal 5: Process data to determine acceptable speed for upcoming road

Previous sections investigated techniques for acquiring information about the vehicle and roadway necessary for estimating the safe speed for traversing an upcoming curve. In this section, the algorithm for processing this information to determine the safe speed is investigated. It should be emphasized that this algorithm is not based on the posted speed limits, but takes into consideration the physics of vehicle, the geometry of the roadway and the pavement conditions. It attempts to calculate maximum speed at which vehicle will be able to safely negotiate the curve.

4.6.1 Safe Speed Estimation

The AASHTO Traffic Engineering Handbook [2] suggests that the following equation be used when designing roadways to govern the relationship between the radius of the curve, the vehicle speed, the curve superelevation (banking), and the coefficient of friction.

$$r = \frac{v^2}{15\,(e+f)}$$

where:

r = radius of the curve (ft.)

v = speed of the vehicle (mph)

e = superelevation of curve (feet/ft. of width)

f = coefficient of friction between the tire and the road (g)

Using this equation, the design speed at any point on the roadway can be calculated if the curve radius, coefficient of friction and superelevation are known. The AASHTO handbook recommends using this equation, along with a conservative value for coefficient of friction (around 0.2) to determine the speed limit for curves. Solving this equation for v and substituting metric for English units, results in the equation:

$$v = 3.117\sqrt{r(e+f)}$$

where:

v = Target speed for a particular road point (m/sec)

r = Radius of curvature at that point (1/m)

e = Superelevation at that point (m/m)

f = Lateral coefficient of friction (g)

The integrated longitudinal countermeasure system tested in Task 3 (and described in detail in the next section) uses this equation to determine the velocity at which it is safe to traverse the upcoming curve. It uses values for the curve radius r and e extracted from a digital map and a value for f provided manually based on current pavement conditions.

4.6.2 Integrated Longitudinal Sensing and Processing Algorithm

This section describes the step-by-step processing performed by the complete longitudinal warning system developed and tested as part of Task 3. Only the sensing and algorithm aspects of the system are presented here. The form and functioning of the various driver interfaces tested are presented in Volume II of this report.

A block diagram depicting the steps of the algorithm are presented in Figure 4-23. The first step is to determine the vehicle's current location (latitude and longitude), using the DGPS system. The vehicle's position on a previously acquired digital map is then determined by locating the road on the map which is closest to the current estimate of the vehicle's position. Starting at this projected point, moving in the direction of travel, the geometry of the upcoming road segment is extracted from the digital map. At a minimum, this information includes a list of points representing the latitude and longitude of the lane center over the length of the roadway equivalent to about 6 seconds of travel time at the current speed. The extracted map data may also include additional information such as road curvature or superelevation, if it is available in the map.

For each point along the upcoming segment of road, the road curvature is calculated (if not known explicitly) by fitting a circular arc through three adjacent road points. Using an estimate of the coefficient of friction and superelevation (assumed to be constant for our experiments), the maximum safe speed (v_t) is calculated for each point along the upcoming road segment using the equation in the previous section.

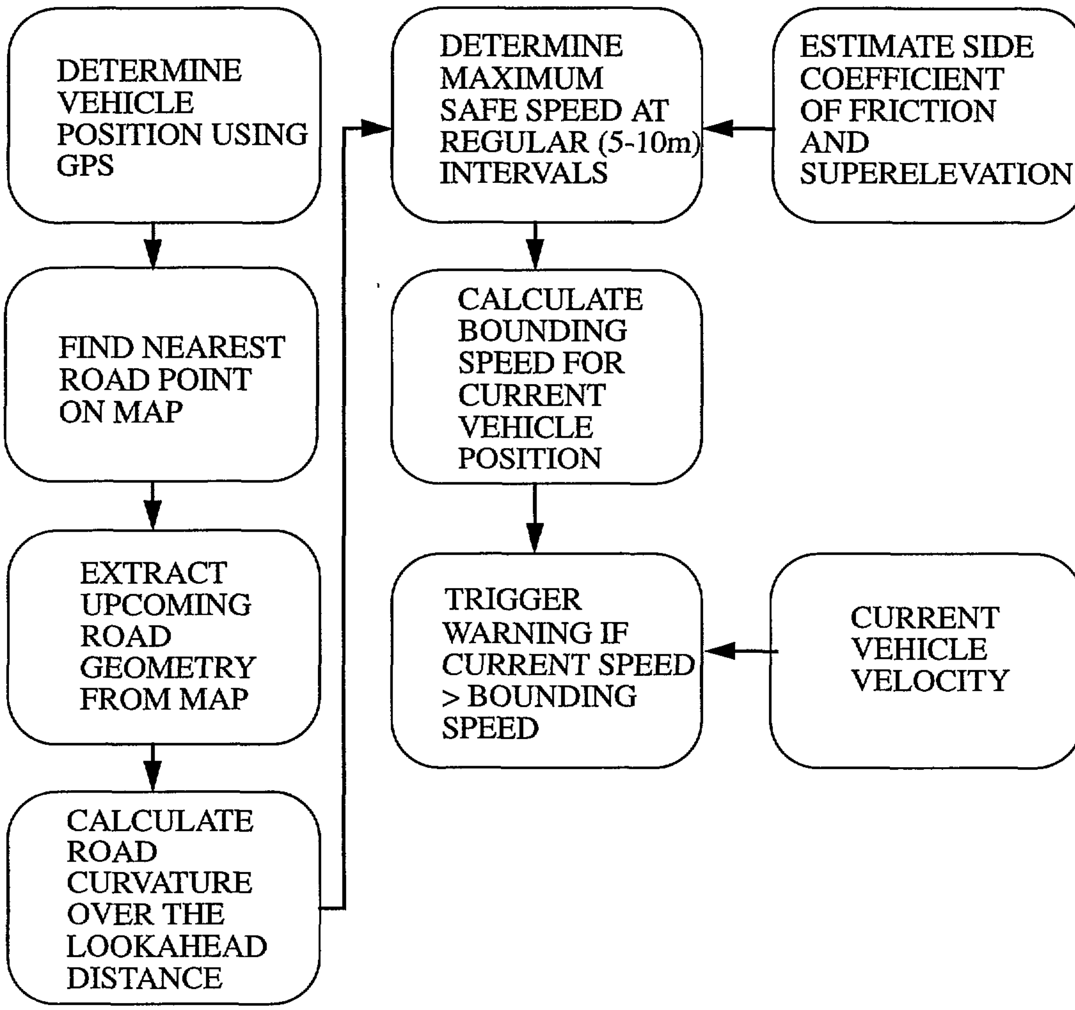

Figure 4-23: Excessive speed warning system algorithm

Next the countermeasure computes the "bounding speed" for the vehicle's current position. The bounding speed (v_b) is the maximum speed at which the vehicle can currently be traveling and still be able to decelerate at a reasonable rate (assumed to be -0.25g) to be at or below the maximum safe speed for each point along the upcoming road segment.

In more detail, for each point along the upcoming road segment, the bounding speed at the current vehicle location is calculated using the following equation:

$$v_b = \sqrt{(v_t)^2 + 2a(d - v_o t_d)}$$

where:

v_b = Bounding speed at the current vehicle location (m/sec)

v_t = Maximum safe speed for the point being considered (m/sec)

a = Assumed driver deceleration (Typically -0.25g)

d = Distance from the current vehicle location to the point being considered

v_0 = Current velocity of the vehicle (m/sec)

t_d = Human braking reaction time (assumed to be 1.5 seconds)

Here, the term $(d-v_o t_d)$ represents the effective distance available for the vehicle to slow down from velocity v_o to the target velocity v_t. The bounding speed for the current vehicle location is considered to be the minimum of all the bounding speeds for the current location calculated using the target speed for all the upcoming road points within the lookahead distance. If the current vehicle speed is above the bounding speed, a warning is triggered to alert the driver of the danger. The form of this warning is described briefly in the next section, and in more detail in Volume II of this report on the Iowa driving simulator experiments.

4.7 Goal 6:Present phased alarm to driver

Once the countermeasure determines there is danger of a roadway departure, the final step is to interact with the driver to avoid the crash. There are a number of alternative interfaces possible for a curve speed warning system, ranging from visual, audible or haptic feedback, to active control intervention in the form of automatic braking. Experiments to test several of these alternatives are described in Volume II of this report. For the in-vehicle tests of the sensors and algorithms described in the next section, a simple audible tone was used to alert the driver of excessive speed for the upcoming curve. The tone had a frequency of lOOOHz, and a duration of 0.5 seconds. Once the warning tone has been presented to the driver, further warnings were suppressed for the following five seconds. This was done to limit irritation to the driver, and was based on the assumption that closely spaced warnings provide little additional information. Tests of this assumption, as well as a more thorough analysis of various driver interface alternatives, are provided in Volume II.

In addition to the audible output, the longitudinal countermeasure system developed for in-vehicle tests contained a graphical user interface, shown in Figure 4-24. It allows the user to modify various parameters such a superelevation, side friction coefficient, lookahead distance etc. To realistically test the system, the vehicle must be driven at high speeds through curves. To avoid this situation, a parameter called speed-factor is used, which artificially inflates the speed at which the system believes the vehicle is currently travelling.

The system has a moving map display system to show the current location of the vehicle (See Figure 4-24). The trace of the vehicle is displayed in different colors to indicate whether a warning was issued at a particular location. The current velocity and the safe velocity are displayed as horizontal bars, which are updated continuously as the vehicle moves. Whenever the length of the safe velocity bar is shorter than the current velocity bar, a warning is triggered.

The system also displays the nearest recorded path or Etak road, the distances to the nearest road and other useful information. The interface allows the user to switch between using the Etak map database and custom-built map databases. Note that most of the information and functionality provided by this interface is diagnostic in nature, and is necessary only for testing and evaluation of the system's performance. A deployed longitudinal countermeasure would probably not require a visual display for the driver, and in fact this type of interface was not included in the Iowa driving simulator experiments described in Volume II.

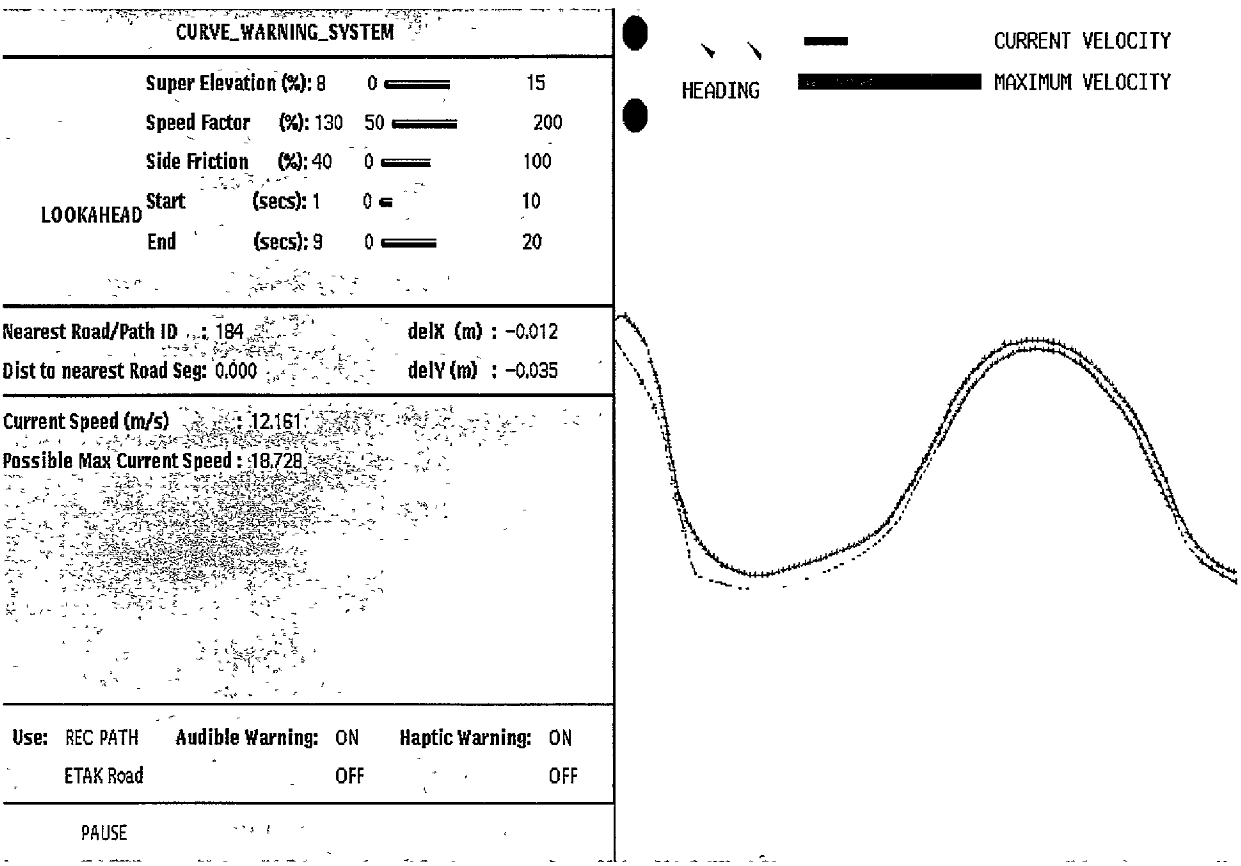

Figure 4-24: User interface for the longitudinal countermeasure

4.8 Results of Integrated tests

The project team implemented an integrated excessive speed through curve warning system based on the individual components discussed in the earlier sections. A block diagram of the system is presented in Figure 4-25. It employs a GPS and a heading gyro to determine the position, orientation and velocity of the vehicle. It uses either the Etak map database, or a custom build map database, to determine the safe speed for the upcoming road segment, according to the equations presented earlier. If the current speed exceeds the safe speed, it triggers an audible alarm. Tests of this system were conducted to determine its performance when all the components tested individually were combined into an integrated system. Of particular importance were repeatability tests. These tests were performed to ascertain the consistency in onset time of warnings provided by the countermeasure.

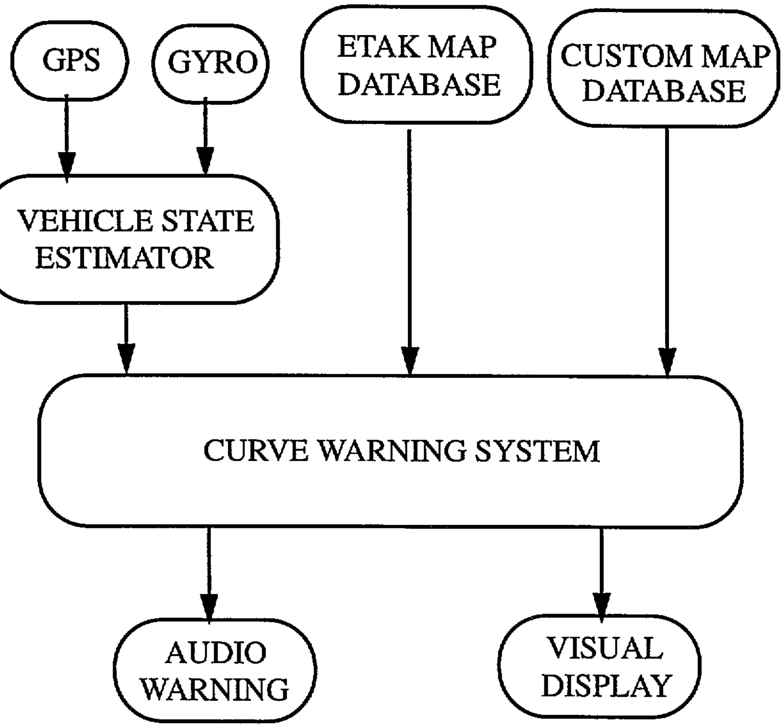

Figure 4-25: Longitudinal countermeasure block diagram

4.8.1 Repeatability of Curve Alert Warnings

A properly implemented warning system should issue warnings in a consistent manner each time the vehicle approaches a curve at too high a speed. To quantify this aspect of countermeasure performance, the following experiment was conducted. The Navlab 5 testbed vehicle was driven repeatedly towards a particular sharp curve at 45 mph. The speed was chosen such that it would result in a warning signal. For each approach to the curve, the time of warning onset relative to the curve entry was recorded. Table 4-8 shows the recorded times for six of the curve approaches. The mean onset time was 3.31 seconds prior to the curve, with a standard deviation of 0.26 seconds. The maximum difference between onset times was 0.65 seconds, which corresponds to a travel distance of approximately 15 meters. To determine the source of this variability, an experiment was conducted to measure the accuracy of the timing technique. In this experiment, the clock was manually started and stopped when the vehicle was passing two different landmarks on the side of the road. The maximum timing variation in this experiment was 0.2 seconds, indicating a substantial portion of the variation in warning onset time, as measured in the original experiment, may have been due to timing inaccuracies and/or variations in vehicle speed.

Table 4-8: Variability of longitudinal countermeasure warning onset time

Run #	Time (sec.)
1	3.11
2	3.53
3	3.45
4	3.61
5	2.96
6	3.18

4.9 Summary

The experiments described in this section indicate that most of the technology exists for a reliable system to warn of excessive speed when approaching curves. Differential GPS technology can provide accurate and reliable estimates of the distance to an upcoming curve. Commercial digital maps, although currently not quite detailed enough, have the potential to provide the necessary geometric information regarding curve sharpness and superelevation. Tests of a system that combines information from GPS and digital maps show that is possible to provide reliable and highly repeatable warning signals when approaching curves at excessive speed.

The biggest missing component for a general longitudinal countermeasure is an effective means of measuring degraded road conditions. Infrastructure-based pavement monitoring systems exist, but are expensive and provide data that is only valid in a local region. Simulation results of vehicle-based methods for inferring the coefficient of friction between the tires and the road appear promising, however these methods require the vehicle to encounter the degraded pavement before it can be detected. Further research is needed before a longitudinal countermeasure capable of handling all roadway conditions can be deployed. Fortunately, the Task 1 analysis conducted for this program indicates that only 10 percent of run-off-road crashes caused by excessive speed occur on snowy or icy roads. The remainder occur on pavement which is dry (64 percent) or wet (26 percent). A system that can simply detect whether the pavement is wet or dry has the potential to prevent most speed related roadway departure crashes. More detailed analysis of the potential effectiveness of longitudinal countermeasures will be conducted in the Task 4.

The other major uncertainty relating to longitudinal countermeasures is the human component. Questions remain about the typical curve negotiation strategy that drivers employ. For instance, when do drivers start to slow down on the approach to a curve, how quickly do they decelerate, and how much is their behavior affected by environmental conditions? Other questions include how will driver's react to a system that provide an excessive speed warning. The latter question is partially addressed in the driving simulator experiments described in Volume II. However, data about curve negotiation habits in naturalistic driving situations remains to be gathered.